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DEVELOPMENT OF AN ATMOSPHERIC MONITORING PLAN FOR SPACE STATION

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ABSTRACT

An environmental health monitoring plan for Space Station will ensure crew health during prolonged habitation. The Space Station, "Freedom" will operate for extended periods, 90+ days, without resupply. A regenerative, closed loop life support system will be utilized in order to minimize resupply logistics and costs. Overboard disposal of wastes and venting of gases to space will be minimal. All waste materials will be treated and recycled. The concentrated wastes will be stabilized and stored for ground disposal. The expected useful life of the station (decades) and the diversity of materials brought aboard for experimental or manufacturing purposes, increases the likelihood of cabin contamination. Processes by which cabin contamination can occur include: biological waste production, material off-gassing, process leakage, accidental containment breach, and accumulation due to poor removal efficiencies of the purification units.

An industrial hygiene approach was taken to rationalize monitoring needs and to identify the substances likely to be present, the amount, and their hazard. This requires a thorough knowledge of the onboard processes, their products and by-products. Many factors influence the monitoring requirements for Space Station: the enclosed space, the recirculation of supply air, the experiences of past missions, the unique experimental and manufacturing facilities, and the interfacing of other modules with the U.S. core modules. Monitor development and selection will be complicated due to the many technologies competing for the life support systems, and the number of experimental payloads under development, each having their own unique monitoring requirements.

Monitoring options include: on-line sensors for process control and determining efficacy of the life support regeneration and purification units; monitors for specific components and contaminants critical for life support; monitors for surrogate parameters representative of contaminant groups likely to be encountered; broad spectrum analyzers capable of identifying and quantifying nearly any contaminant for leak detection and remedial action; manual aboard sampling and analysis; and sample collection/preservation with ground based analysis. Other factors considered in the monitoring plan include: results of on ground system tests; consequences of contaminant detection failure; instrument parameters such as weight, volume, reliability, specificity, detection limit, and maintenance requirements; crew time and effort; expendables; and waste production.

INDUSTRIAL HYGIENE PERSPECTIVE

It is standard practice in industry to monitor for those agents in the workplace that may occur at levels approaching or exceeding safe limits. Defining those limits and deciding on which agents to monitor, calls for a systematic and thorough approach, often employed in the field of industrial hygiene.

Industrial Hygiene is the science and art devoted to the anticipation, recognition, evaluation, and control of environmental factors and stresses arising in or from the workplace that may cause sickness, impair health and well being, discomfort or inefficiency among workers, their families or members of the community at large.[1]

Work hazards should be anticipated before they exist and action must be taken to prevent their occurrence, so no individual is placed at undue risk. Recognition of potential hazards requires familarity with the process and work operations involved, the maintenance of an inventory of agents, a periodic review of the job activities, and the effectiveness of control measures.

Evaluation principally involves performing the monitoring to determine the exposures, comparing the results with standards, and communicating the judgement on the degree of hazard with the individuals affected and those in authority to take corrective action. Monitoring is a continuing program of observation and judgement. Reasons for monitoring are: to determine exposure levels; to determine effectiveness of control measures; to detect process changes; to investigate complaints; and to confirm compliance with standards.

In monitoring, part of the environment is sampled and the quality of the whole environment is inferred. A number of factors must be considered in order to take a representative sample. In industry the concern is worker exposure, so air samples are taken in the breathing zone of the worker, specified as twelve inches from the nose. Data from such personal samples are better correlated with exposures than any other type because of large concentration gradients and awkward operator/machine interfaces that can occur in industry. Sampling general workroom air is effective when the emission rates are uniform and there is good mixing. However, when relying on area sampling, documentation of its correlation with personal samples must be available. Sampling at the operation usually yields the highest concentration and worst case exposures. Rest areas should be occasionally monitored to confirm a clean zone of zero exposure.

All individuals exposed at or above the action level must be monitored. The action level is some fraction of the standard below which exposures must remain, usually one-half or one-fourth the standard. It is prudent to monitor nearby workers and complainers, as they may be sensitive to the agent, or an unidentified process leak may be present, or a control device may have failed.

Sample duration depends on the detection limit of the technique used for analysis, the standard, and the estimated air concentration. The sample duration should represent an identifiable period, consistent with the standard, the work shift and the process. Common sample durations are eight hours, for time weighted average standards and ten minutes for peak concentrations. Continuous monitoring is required if ceiling values are likely to be exceeded or when conditions immediately dangerous to life and health may occur.

Monitoring results are compared with standards to determine the severity of the exposure and a plan of action. Standards which must be met are the Permissible Exposure Limits (PEL's) published by the Occupational Safety and Health Administration (OSHA).[2] These are legal standards and represent the minimum effort required to maintain a safe and healthful workplace. Other standards or guidelines are recommended by professional organizations and consensus groups. Most widely used are the Threshold Limit Values (TLV's) of the American Conference of Governmental Industrial Hygienists (ACGIH).[3] Most PEL's were adopted from TLV's and most are eight hour time weighted average or ceiling values. For each standard there is a criteria document which presents data on which the standard is based.

Control can be achieved by reducing the emission source, interrupting the air path, and protecting the receiver. Specific control methods are: elimination or substitution with a less harmful agent; process change; enclosure of the process or source; isolation in time or distance; wet methods to reduce dust loadings and to scrub gases; local exhaust ventilation to remove the contaminant at its source; dilution ventilation; housekeeping; adequate maintenance; training and education of workers; area and personal monitoring; and use of personal protective equipment, mainly as backup for harmful or life threatening situations.

Elimination, substitution, and process change are ground based decisions that must be made well before flight. Strict flight requirements are being relaxed to allow the use of off the shelf items for Space Station. Isolation, wet methods, and dilution are not compatible with space vehicles. During space flight, control methods will rely heavily on enclosure, venting to the trace contaminant control system, housekeeping, and monitoring to assure a healthy cabin environment.

Supplied Breathing Air

On ground, when we encounter situations with probabilities of oxygen deficiencies or conditions immediately dangerous to life and health, breathing air must be supplied.[4] It must be Grade D or better, with specifications as follows: oxygen 19-23%, carbon monoxide (CO) ≤20 ppm, carbon dioxide (CO_2) ≤1000 ppm, condensed hydrocarbons ≤5 mg/M^3, and the water content must be stated. The air source is ambient air, supplied by a compressor to a delivery system or cylinder for storage. Any one of these can be a source of contamination. A frequently encountered cause of morbidity from contaminated air is carbon monoxide, from the incomplete oxidation of hydrocarbons of the compressor fuel, exhaust, and lubricants. Another source is from over heating of charcoal filters used for purifying the intake air. For this reason, continuous carbon monoxide and/or temperature monitors are required on air supply compressors. The condensed hydrocarbons can cause lipoid pneumonia and decrease the gas exchange membrane surface in the lung. They may also oxidize to CO and CO_2 within the storage cylinders. The water content is important: if excessive, it can cause regulator valves to clog or freeze, and promote cylinder corrosion; and if the air is too dry then irritation of mucous membranes, eyes, nose, and throat can occur. The oxygen (O_2) content should be checked routinely to confirm adequate concentrations. Industrial users check every cylinder of air before use, since several fatal incidents have occurred due to low oxygen concentrations.

Confined Spaces

In confined spaces, an area is enclosed or partially enclosed with poor ventilation and mixing with the outside air is limited. Before entry, the atmosphere should be tested to ensure the O_2 concentration is 19.5-21%. Toxic, flammable, and oxygen displacing gases and vapors should also be monitored. Common contaminants to check are hydrogen sulfide (H_2S), CO, CO_2, and methane (CH_4), plus any other material that is likely to be present because of prior storage. If conditions immediately dangerous to life and health are probable, then continuous monitoring is required, since conditions within a confined space can change rapidly.[5]

Nuclear Submarines

Submarines are enclosed environments with controlled atmospheres and are capable of remaining submerged for extended periods. Each submarine is equipped with a monitoring system designed to measure gaseous atmospheric constituents which are important in life support, called the Central Atmosphere Monitoring System (CAMS-I). It continuously analyzes air from the main fan room for eight substances, with a mass spectrometer (MS) and an infrared analyzer (IR). The mass spectrometer looks at specific m/e in the range of 2-300 amu. The average failure time was reported to be 3500 hours.[6] It is considered a monitor and not a trace contaminant detector, since sensitivity was restricted to meet stability and dependability requirements. CAMS-II is under development.[7] It will use a scanning mass spectrometer to measure 12 substances continuously from multiple sample ports located throughout the submarine. The MS will measure:

non-methane aliphatic hydrocarbons	0-100 ppm
aromatic hydrocarbons	0-10 ppm
benzene	0-10 ppm
carbon dioxide	0-3.3 %
hydrogen	0-5 %
nitrogen	0-80 %
oxygen	0-25 %
refrigerant R-11	0-1200 ppm
refrigerant R-12	0-1200 ppm
trichloroethylene	0-100 ppm
water vapor	0-4 %

Since the MS cannot resolve CO and N_2, as both have m/e of 28, an IR measures for CO. CO is a major concern in submarines because of combustion processes, smoking, cooking, and smoldering of activated charcoal filters designed to remove odors, refrigerants, and hydrocarbons. Refrigerants themselves are of little concern, however their decomposition products from compressors or fire are corrosive, toxic, and will poison the catalytic oxidizer. Also on board is a paramagnetic O_2 analyzer and a Dwyer CO_2 analyzer. A portable photoionization detector is used for hydrocarbons, it is referred to as the "trace gas analyzer." Earlier CAMS used a gas chromatograph with a flame ionization detector as a hydrocarbon detector in which 100 ml samples were injected. It was not compatible with submarine duty.[8] An assortment of Draeger detector tubes are used for leak detection and for CAMS backup.

MONITORING ON SHUTTLE

The air revitalization system and many other systems on the Shuttle are different from those proposed for Space Station.[9] On the Shuttle, CO_2 is removed by LiOH canisters which are changed when the CO_2 concentration is 50 mm of Hg, or every 12 hours. Activated charcoal filters are used to remove hydrocarbons and odors. Carbon monoxide is oxidized to CO_2 in a low temperature catalytic oxidizer, located downstream from the humidity and thermal control unit. The activated charcoal filters and the low temperature catalytic oxidizer are capable of removing most contaminants that may occur. Fresh air is supplied from cryogenic liquid nitrogen (N_2) and (O_2) stored on board. Thus on the Shuttle, continuous monitoring is done for total pressure, temperature, humidity, O_2, and CO_2. Air samples are taken in evacuated bottles, and by active collection on various sorbent tubes, such as charcoal, tenax, and molecular sieve. Those samples are post-flight analyzed in ground based laboratories. The charcoal and LiOH air purification filters are also often analyzed for contaminants.

MONITORING NEEDS

Experiences of past missions and ground based systems tests have identified a number of health concerns that should be addressed in a monitoring plan for Space Station. Paramount is the flight and post flight health complaints of the crews: headache; irritation of the eyes and upper respiratory tract; and odor complaints, symptomatic of noxious air.[10] Early missions had insufficient monitoring data for evaluation, which indicated a need for a more comprehensive monitoring system. Analyses of activated carbon and lithium hydroxide filters of the atmospheric revitalization systems, and the active sampling and analysis for air contaminants of later missions have identified over 250 contaminants in spacecraft air.[11] Most were observed at trace levels, well below the Spacecraft Maximum Allowable Concentration (SMAC). Others may have elicited symptoms among crew members, may accumulate to harmful levels, or may have potential to poison the spacecraft life support system.

Nitrogen tetroxide (N_2O_4), hydrazine, and monomethyl hydrazine are the main liquid propellants to be used on Space Station. Because of the quantities involved and the frequency of extra vehicular activity (EVA), some Space Station contamination will occur. An air lock will likely serve as a decontamination station and will contain a propellant monitor. If elevated propellant concentrations are detected in the air lock, then that atmosphere will be dumped to space to prevent contamination of the cabin atmosphere. The air revitalization and trace contaminant control systems were not designed to handle high pollutant loads. Some N_2O_4 contamination occurred on Apollo-Soyuz.[10]

Halon 1301 is the fire suppressant to be used on Space Station. Halon was detected on spacelab mission SL-1 and on Shuttle missions STS-3, and STS-4. The trace contaminant control system (TCCS) will only handle modest quantities. Halon degradation products are toxic and will poison the catalytic oxidizer. If a halon release occurs it will be necessary to vent the cabin air to space and repressurize.

Methane is a metabolic product which usually accumulates as each mission progresses. It will likely be the contaminant of greatest concentration. The Bosch CO_2 reduction system, a candidate for the air revitalization system (ARS), will produce large quantities of methane. A high temperature catalytic oxidizer will be required to keep CH_4 concentrations below 1 ppm.[12,13]

CO, a product of incomplete combustion, may be released from metabolic processes, smoldering of carbon filters, or fire. The Bosch CO_2 reduction system produces CO and the potential for rapid accumulation exists, if not removed by the trace contaminant control system.[12,13]

Ammonia (NH_3), a product of metabolism will be released from urine processing, and it is probably a degradation product of the solid amine resin proposed for the ARS.[14] Phosphoric acid impregnated charcoal filters can remove NH_3.

Hydrogen (H_2) will be produced by electrolysis and used in CO_2 reduction by both the Bosch and the Sabatier processes.[12,13,15] A pressure gradient will be used to minimize the likelihood of explosive mixtures from developing, if a leak occurs.

Toluene was detected on a number of missions. On Shuttle mission STS-2, toluene approached the SMAC value in one sample. Subsequent analyses indicated that for the sample, the additive toxicity hazard index for systemic poisons was exceeded by 1.22 times, with toluene the major constituent.[10] Toluene is also a contaminant which off gases from the solid amine resin of the ARS.[14]

Trimethylamine is a principal breakdown product of the solid amine resin of the ARS. The trimethylamine concentration has exceeded safe limits in tests of the ARS.[14] Because of the numerous trace organics off gassing from solid amine process a post sorbent bed such as phosphoric acid impregnated charcoal will be used.

Glutaraldehyde and silicon escaped containment on Spacelab mission SL-D1. Glutaraldehyde is a preservative and disinfectant with irritating properties. It may also be used in electrophoresis experiments on Space Station. Silicon compounds are catalyst poisons and will occur on Space Station.

Freons have been detected on all Shuttle missions.[16] The degradation products are corrosive, irritating, toxic, and catalyst poisons. Freon 12 will be on Space Station.

A computer model developed from Shuttle charcoal canister analysis for TCCS contaminant removal studies indicated that five contaminants may exceed SMAC values: propenal (acrolein), an irritant; benzene, a systemic poison and carcinogen; o-diethylphthalate, an irritant; propylfluorosilane, an irritant and catalyst poison; and 2-methylhexane, a central nervous system depressant.[17] Benzene has also temporarily exceeded SMAC values during preflight off gassing tests.[16]

Ethanal (acetaldehyde), ethanol, dichloromethane, and acetone have a high frequency of occurrence on shuttle missions and are likely to be present on Space Station.[16]

Oxidation products will be produced in the catalytic oxidizer. Post sorbent beds are necessary to prevent the release of oxidants and free radicals to the cabin air from the TCCS. Also, it has been hypothesized that secondary pollutants are important in cabin atmospheres. Trial simulations have indicated that spacecraft cabins may develop elevated NO_2 concentrations and ozone (O_3) concentrations exceeding SMAC values.[18] Oxidation products, NO_2, O_3, and formaldehyde, were among the contaminants suspected of causing irritation on Shuttle flights, although particulates from biological sources were the undisputed cause of crew discomfort.[19]

Major metabolic products which must be removed by the ARS and the TCCS are CO, CO_2, NH_3, H_2S, CH_4, organic acids, and mercaptans.[20]

Foul odors have been observed on a number of missions. Many were attributable to metabolic products. An unusual odor and crew headaches occurred on Shuttle flight STS-6. Burnt wire insulation from an electrical short was the suspected causal agent.[10] Electrical fire can produce a number of noxious agents including halogenated organics, benzene derivatives, nitriles, and cyanates.[21] Space Station design must be able to handle such contingencies either through the TCCS or a smoke removal unit,[22] without having to rely on venting the cabin air to space and repressurizing.

For fire safety concerns, Halon 1301 will be used for fire suppression, followed by venting cabin air to space and repressurizing. Smoke detectors are an integral part of the fire detection and suppression system. To protect from toxic combustion products, infrared monitors are recommended for CO, hydrogen fluoride (HF), and hydrogen cyanide (HCN).[23]

Volatiles will be released to the atmosphere from electrolysis and from phase change urine processing. Carboxylic acids and phenols will be major contaminants.[24,25] Iodination products from the water disinfection process may cross the air/water interface and permeate the entire life support environment. The identity of these products, their expected concentrations, and their medical effects are largely unknown.[26] However, I suspect the byproduct concentrations and effects of iodination are less than those resulting from chlorination.

SPACE STATION CONFIGURATION

Space Station is designed to operate for extended periods, 90 plus days, without resupply. A regenerative, nearly closed loop life support system will be required to minimize resupply logistics and costs. Overboard disposal of wastes and venting of gases to space will be minimal. All waste materials will be treated and recycled. The concentrated wastes will be stabilized and stored for ground disposal. The expected useful life of the station is decades and a diversity of materials will be brought aboard for experimental or manufacturing purposes. The likelihood of cabin contamination is great. Cabin contamination can occur from a number of sources: biological waste production, material off gassing, process leakage, accidental containment breach, and accumulation due to poor removal efficiencies of the purification units.

The Space Station, "Freedom," will have four modules: the U.S. Laboratory (USLAB); the U.S. Habitation module (USHAB); the Japanese Experimental Module (JEM); and the European Space Agency (ESA) module, Columbus. The modules are connected by four resource nodes. Two airlocks and a logistics module are connected to the resource nodes. Each module will have an independent Environmental Control Life Support System (ECLSS), complete with a Trace Contaminant Control System (TCCS). The U.S. modules will have four Air Revitalization Systems (ARS), two in each module. Each ARS is designed to support four crew members; One ARS at a time will operate in each module.

The ARS will provide ventilation to each module and node but not to the airlocks. Intramodule circulation will approximate near perfect mixing. Intermodule air exchange design is 130 cubic feet per minute (CFM) through 4-4.5 inch ducts.[27] The ventilation design is primarily based on: heat transfer and humidity control to maintain crew comfort; and O_2 supply and CO_2 removal requirements to maintain a healthful atmosphere.[28] The air exchange rate will be 1-2 years, achieved through air loss from leakage and airlock EVA.

ESA Columbus Module

ESA Columbus monitoring requirements are based on the fact, that the types of contaminants and their buildup characteristics are not precisely known, and that safety will require the monitoring of all contaminants permanently.[29] Hence, ESA is developing, for Columbus, a GC/MS to monitor N_2, CO_2, O_2, H_2O, plus a lengthy target list of trace contaminants. The contaminant list includes 15 alcohols, 5 aldehydes, 12 aromatics, 11 esters, 3 ethers, 21 halocarbons, 37 hydrocarbons, 8 ketones, and 11 miscellaneous compounds , such as NH_3, CO, H_2S, H_2, O_3, SO_2, NO, and NO_2.

Japanese Experimental Module

The 70 M^3 JEM and its 24 M^3 logistics module are designed for two crew members.[30] The JEM will have an independent ECLSS interfaced with the Space Station core. However, concentrated CO_2 will be returned to U.S. modules for processing, and wastewater will be returned to the U.S. modules for processing and H_2O recovery. Its TCCS design is based on a contaminant load of 15.4 grams/day.[31]

The JEM will continuously monitor for total pressure, temperature, humidity, O_2, and CO_2. The JEM will rely on the U.S. modules for trace gas analysis via sample lines. A GC/MS is expected.

U.S. Modules

The U.S modules will provide facilities for on-orbit repair, health maintenance, and a number of material processing and biological experiments intended to lead to manufacturing in space.

A maintenance work station will allow on-orbit repair of defective or damaged hardware. Processes likely to be required are drilling, sawing, welding, soldering, and epoxy gluing. A work bench/contaminant control console is envisioned that will collect the particulate and gaseous emissions generated in the repair process near their source.[32] The rack would be equipped with filters and the air recirculated with some venting to the TCCS. The work station would be a source of particulates, metal fumes, and gases not encountered on prior missions.

The health maintenance facility will provide critical care for one individual for 28 days and outpatient care for the crew complement for the mission duration. The equipment and supply list for this facility will be lengthy.[33] It may be an additional source of trace contaminants, mainly sterilants.

The U.S. Laboratory will provide facilities for experiments and manufacturing.[34] The on board processes will generate biologicals, combustion and oxidation products, acid gases, metal and crystal fumes, and assorted lab wastes. Many of these materials are capable of adversely affecting the ECLSS subsystems by poisoning the catalyst or absorption beds, or they could appear in the humidity condensate, the potable water supply. Materials will have to be stored, then transported to the point of use, and the waste products handled. The lab racks will be contained with at least a two failure tolerant design. They will be equipped with some type of contaminant control equipment and vented to the TCCS. The lab racks should be equipped with monitors, specific for the process they contain to detect internal leaks. The chemical storage area should be monitored, and the cabin atmosphere must be sampled to alert the crew of any leak.

Trace Contaminant Control System

The technology base for the TCCS is good. Only limited system tests have been conducted but they have worked as predicted. The TCCS will consist of fixed bed charcoal filters, high efficiency particulate filters, and a high temperature (680 °C) catalytic oxidizer (palladium/aluminum) with pre and post sorbent beds of LiOH. There will be four units, two in each module. The air flow through each catalytic oxidizer is 2.5 CFM, or 5 CFM for the two U.S. modules.[12] This is only 4 air changes per day of what should be considered as fresh air. It may be too low. The TCCS will receive cabin air from the temperature and humidity control system. Purge gases from the ARS, waste water recovery, urine processing, waste reduction and storage systems, and lab racks are to be routed to the TCCS for contaminant removal. For comparison, the indoor air quality ventilation guideline is 15 CFM per person.[35] The guideline is intended to keep odors to an acceptable level to 80% of the visitors entering the space and it assumes that one third of the occupants are smoking at the rate of 2.2 cigarettes per hour.

TECHNOLOGY ASSESSMENT

A technology assessment study on monitoring systems was performed by Battelle Columbus Division for NASA.[11] They recommended: 1) a long path Fourier transform infrared (FTIR) analyzer for rapid detection of high risk contamination incidents, and 2) a GC/MS with mass selective or ion-trap technologies for detailed monitoring of extended crew exposures to low (ppb) contaminations. Priority requirements for rating the candidate monitoring systems were: real time output, which is particularly important in closed environments and long duration missions; ability to detect and quantify a wide range and number of volatile compounds; ability to trigger a warning when the SMAC is approached; and the ability to monitor several modules and airlocks simultaneously. In the assessment, many instrument parameters were considered, each weighted equally: weight, volume, power requirements, sensitivity, dynamic range, response time, selectivity, growth capability, crew time, by-product generation, consumables, reliability, and maintenance. Instruments and systems considered included: CAMS, long path FTIR, matrix isolation FTIR, GC/MS, GC/photoionization detector, electrochemical devices, and chemiluminescent monitors. Long path FTIR and GC/MS appeared to be the most promising technologies for Space Station monitoring. However, several critical questions are yet to be answered: what is the target list of compounds to be monitored; which must be monitored on a continuous real time basis; at what concentration ranges; and in how many locations?

CONCLUSIONS

Development of the monitoring plan for Space Station will be a continuing process. The monitoring system must be adaptable to accommodate new parameters and concentration ranges. All agents should be monitored that have a reasonable probability of occurrence at or above some action level, such one-half the SMAC. The analytical method relied upon must be able to quantify at action level concentrations. The basis for monitoring should be the contaminants: toxicity, quantities or production rates, removal efficiencies of the ECLSS system, and capacity to poison the ECLSS system.

Monitoring for all contaminants at multiple sites and at part per billion concentrations is impracticable and should not be attempted. Monitoring for a contaminant should not be done simply because there is an assigned SMAC. Equipment control monitors, and the monitoring of a surrogate parameter as a substitute for the etiological agent should not be relied upon when making health evaluations.

A GC/MS should be developed for Space Station. It should be a fixed instrument that continuously samples the well mixed cabin return air. It should have a sample line to each module and airlock for routine comparison of atmospheres from remote sections of the spacecraft. It should be capable of monitoring for major atmospheric components (e.g. N_2, O_2, CO_2, H_2O, H_2, CO, CH_4, and Halon 1301) and numerous trace gases (e.g. hydrocarbons, halocarbons, silanes, and phenols).

A LP/FTIR could detect modest levels of many compounds not readily amendable to GC/MS analyses (e.g. inorganics, acid and basic gases, oxidation products, and CO). It could also serve as a trace hydrocarbon detector.

A portable hand held hydrocarbon detector should be available for leak detection in remote areas of the spacecraft. A TLV Sniffer (has good response for CH4) or H-Nu photoionization type instrument can detect low ppm concentrations of hydrocarbons and should be adequate for this purpose.

Redundant monitors should be present for critical parameters: IR for CO; IR or electrochemical for CO_2; and electrochemical for O_2.

Particulates and fumes could be measured by either photometric or piezoelectric aerosol monitors. Sample collection and ground based analyses will be necessary for verifying mass loadings, particle size distributions, and chemical components often present particle bound (metals, semi-volatile and non-volatile compounds).

Each experiment and manufacturing process must be evaluated for possible sources of cabin contamination. The lab racks should be equipped with monitoring devices specific to the process being contained. There are many miniature photometric, IR, and electrochemical devices which could serve this need.

Finally, sample collection and preservation will have to be continued for ground based analyses, to confirm the accuracy and reliability of the on board monitoring system.

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